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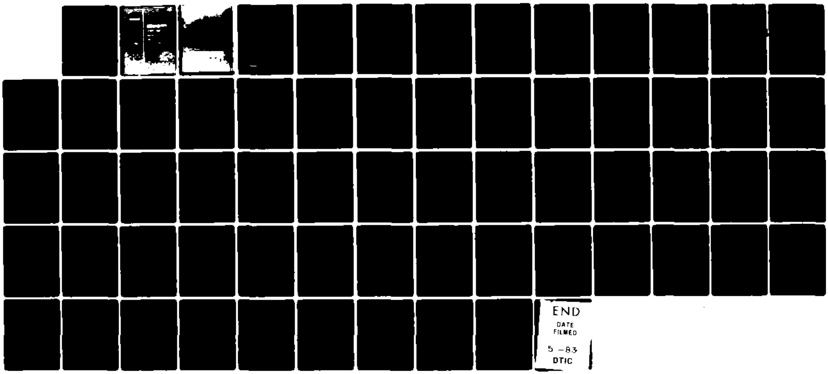

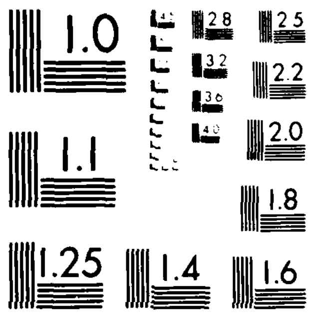

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A RAND NOTE

NON-NUCLEAR AIR-TO-SURFACE ORDNANCE FOR THE FUTURE: AN APPROACH TO PROPULSION TECHNOLOGY RISK ASSESSMENT

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SANTA MONICA, CA. 90406

Proposes a risk assessment method that addresses the likelihood of achieving technological advances for particular military hardware by quantifying (1) the technological state-of-the-art of that hardware and (2) the probability of achieving that program relative to past experiences with similar programs. The hardware considered in this research for state-of-the-art trending and risk assessment includes man-rated aircraft turbine engines, solid rocket motors, and non-man-rated missile and drone turbine engines. Preliminary evaluation of the various models indicates that, for the most part, the results agree with what engineers would expect concerning variables that are important to the trend of the technologies and to the outcomes for particular programs.

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PREFACE

This Rand Note presents the initial results of research to provide military weapon planners with improved tools and techniques for the quantitative assessment of risk in new weapon programs. The work was conducted as part of a Project AIR FORCE study of non-nuclear air-to-surface ordnance for the future under the Technology Applications Program.

The risk assessment method proposed here addresses the likelihood of achieving technological advances for particular military hardware by quantifying (1) the technological state of the art of that hardware and (2) the probability of achieving that program relative to past experiences with similar programs. The hardware considered in this research for state-of-the-art trending and risk assessment includes man-rated aircraft turbine engines, solid rocket motors, and non-man-rated missile and drone turbine engines.

This research should be of interest to Air Force planners in the Aeronautical Systems Division, Armament Division, Air Force Systems Command, Tactical Air Command, and United States Air Force Headquarters.

A

SUMMARY

Air delivery of munitions against surface targets constitutes a critical part of the warfighting capability of an air force. Improvements in ordnance may produce efficient "force multipliers" for conventional theater conflicts. Significant technological advances in the airframe, propulsion, guidance, and warhead designs for new munitions are expected during the next decade.

Programs must be designed to advance these new technologies to the point where they can be used to develop weapons that will provide new warfighting capabilities. Long-range planning to achieve timely new weapon-system capability most efficiently requires methods and techniques that address the technological evolution of key components and the risk associated with introducing evolving technologies into weapon programs.

This Rand Note presents a method to quantify the risk inherent in seeking higher levels of subsystem performance. This method, which we apply specifically to the propulsion technology of aircraft and air-to-surface ordnance, uses a two-step approach involving (1) time trending of the state of the art of subsystem technology by identifying appropriate variables that characterize the technology and (2) obtaining a risk measure that reflects the probability that a program meets its performance and schedule goals.

We first constructed a comprehensive data base for propulsion systems used in manned and non-manned applications. Time-trending models were obtained for man-rated and non-man-rated air-breathing

engines (separately and combined), solid rocket motors, and a combination of solid motors and non-man-rated air-breathing engines. The models appear to be reasonable representations of evolutionary technological progress for air-breathing and non-air-breathing propulsion for aircraft, missiles, and drones. The models' independent variables behave consistently with what is expected from engineering judgment about the technology represented.

We selected a logistic model to estimate the probability of meeting the specific performance and schedule goals--i.e., the program "risk." For tactical missiles using solid rocket motors, we evaluated two models: one derived from 28 solid rocket motors and one derived from the combination of 28 solid rocket motors and 9 non-man-rated air-breathing engines. Technology is easier to characterize and risk is easier to measure when the data are homogeneous. More research is needed, however, to combine disparate data bases.

Program risk (i.e., the probability of not achieving specified performance goals on schedule) was calculated for specific programs. The results were intuitively satisfying in most cases. For instance, the Maverick solid rocket motor was considered to be technologically conservative at the start of the program, and it was a straightforward, successful development. The success probability calculated for Maverick using data for the 28 solid rocket motors was greater than .95, indicating a conservative program.

The F-100 aircraft turbine engine was evaluated using the combined man-rated and non-man-rated air-breathing engine time trend and risk analyses. This engine was acknowledged to represent a significant technological advance when selected to power the F-15 aircraft in 1970.

We calculate a probability of less than .01 for it when it passed its development milestone in 1974, indicating a highly advanced and technologically risky program. The engine continues to require development in the field.

The analysis approach developed in this study is intended to provide quantitative information as a decision aid to weapon system planners; it does not replace the current decisionmaking process. Nor is it intended to be used simply to foreclose new technological opportunities.

Given a decision that a higher performance level is needed, the information provided by this approach would prepare decisionmakers for the possibility of less favorable outcomes in "riskier" programs, which are likely to take longer, cost more, and provide less performance than originally planned. Decisionmakers could then make allowances for such outcomes for subsystems, and equally important, they could also make adjustments to the entire weapon system program if the subsystem were the pacing development item.

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I. INTRODUCTION

Air-delivered munitions employed against surface targets constitute a critical part of the warfighting capability of an air force. Improvements in ordnance may produce efficient "force multipliers" in conventional theater conflicts. Significant technological advances in the airframe, propulsion, guidance, sensor, fuzing, countermeasure, and warhead designs for new munitions are expected during the next decade. Programs must be designed to advance these technologies to the point where they can be used to develop weapons that will provide new warfighting capabilities.

Future tactical air-delivered munition inventories must include a family of standoff weapons. Such weapons are needed to provide a capability at least against fixed targets such as air bases, bridges, SAM radars, missile sites, and air base defenses. These munitions are expected to be costly.

The Navy Harpoon, with a range of about 60 miles, costs about $750,000 per unit in the FY-1983 budget. The Air Force air-launched cruise missile (ALCM) is approaching $1.5 million per copy in its strategic application. Standoff weapons intended to achieve tactical combat tasks such as defense suppression or air base attack must be considered carefully as to total program cost and effectiveness.

Future standoff weapons may require new technologies in propulsion. Examples of new concepts include multiple-radial-pulse rocket motors with minimum smoke, integral rocket-ramjets and ducted rockets, and expendable subsonic and supersonic turbojet or turbofan engines. New

concepts and levels of complexity may make propulsion the pacing development subsystem in tactical missiles. Indeed, propulsion has been the pacing subsystem in manned aircraft systems, as well as in strategic air-launched missiles such as SRAM (solid rocket motor) and Quail (turbojet).

Timely and efficient development of new weapon system capability requires methods and techniques that address the technological evolution of key components and the risk associated with introducing evolving technologies into weapon programs. This Rand Note presents a risk-assessment methodology, applied specifically to the propulsion technology of air-to-surface ordnance.

To assess the risk of a new propulsion subsystem in a new missile program, this study (1) surveys and reviews pertinent propulsion technologies and programs, (2) constructs an appropriate data base of aircraft and missile propulsion programs, (3) estimates an evolutionary time trending of propulsion technology by appropriately quantifying the state of the art, and (4) develops an analytical technique to quantify the risk in a particular propulsion program.

To establish a quantitative approach to evolutionary technology trending for the spectrum of propulsion concepts, we document the experience gained in developing air-breathing and non-air-breathing propulsion and then conduct a preliminary analysis to quantify risk assessment in such a development program. The initial effort included man-rated air-breathing propulsion to take advantage of the significant data base created for earlier Rand studies.

Similar data bases were collected for solid and liquid rockets, ramjets and ducted rockets, and turbojets and turbofans for non-man-

rated missile and drone applications. The effort concentrated on air-breathing turbine engines and solid rocket motors as representing the extremes of the propulsion range for air-to-surface ordnance. Few liquid rocket and ramjet engines have been developed for tactical missiles during the past four decades.

Section II discusses propulsion trends during the past four decades. Section III presents our techniques and the data base used to quantify evolutionary technology trends and to provide a quantitative approach to propulsion program risk assessment. Section IV summarizes experience gained to date and the desirable direction of future work.

II. OVERVIEW OF PROPULSION TECHNOLOGIES FOR FUTURE TACTICAL MISSILES[1]

A wide spectrum of propulsion choices is potentially available for tactical missiles for the 1990s. Technology improvements in air-breathing turbine engines, in hybrids such as the integral rocket ramjet and ducted rocket, and in non-air-breathing solid and liquid rockets are expected to provide improved performance and reliability while lowering life-cycle costs. These improvements will come in the form of new design technologies, higher-energy propellants, stronger and lighter materials, and efficient manufacturing processes.

All USAF tactical air-to-surface munitions are now unpowered or powered by solid-propellant rockets. Until recently, the air-launched propelled tactical munitions of all the military services used solid motors or occasionally prepackaged liquid motors. The Navy Harpoon missile was the first air-launched, air-breathing propelled tactical munition to be developed, produced, and deployed in the United States.

Tactical-missile development during the past three decades has relied largely on non-air-breathing propulsion because tactical missiles have not needed other than the limited performance provided by solid and, occasionally, prepackaged liquid rocket motors. Table 1 lists the strategic and tactical/theater powered missile programs that reached operational status during this period. Tactical applications have been

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[1]This section is based on discussions with personnel at the Air Force Aeropropulsion Laboratory, Air Force Rocket Propulsion Laboratory, Joint Cruise Missile Program Office, Chemical Propulsion Information Agency, Naval Weapons Center, Aerojet, Atlantic Research, Booz-Allen & Hamilton, Detroit Diesel Allison, General Electric, Hercules, Hughes, Marquardt, McDonnell-Douglas, Rocketdyne, Teledyne, Thiokol, and Williams International between November 1981 and June 1982.

Table 1

OPERATIONAL POWERED-MISSILE PROGRAMS

1950s	1960s	1970s
	Strategic	
Snark (TJ)	Minuteman I,II (SR)	Minuteman III (SR)
Atlas (LR)	Titan (LR)	SRAM (SR)
Thor (LR)	Quail (TJ)	Poseidon (SR)
Jupiter (LR)	Hound Dog (TJ)	
Regulus (TJ)	Polaris (SR)	
Rascal (LR)		
	Tactical/Theater	
Corporal (LR)	Sergeant (SR)	Lance (LR)
Redstone (LR)	Pershing I (SR)	Improved Sidewinder (SR)
Honest John (SR)	Shrike (SR)	Improved Sparrow (SR)
Bomarc (RJ)	Dragon (SR)	Harpoon (TJ)
Falcon (SR)	Chaparral (SR)	Harm (SR)
Matador (TJ)	Standard (SR)	Tow (SR)
Mace (TJ)		Maverick (SR)
Sidewinder (SR)		Phoenix (SR)
Sparrow (SR)		Hellfire (SR)
Bullpup (LR)		Stinger (SR)
Hawk I (SR)		Patriot (SR)
Terrier (SR)		Hawk II (SR)
Tartar (SR)		Standard ARM (SR)
Talos (RJ)		
Genie (SR)		
Lacrosse (SR)		
Nike (SR)		

NOTE: LR = liquid rocket
RJ = ramjet
SR - solid rocket
TJ = turbojet

dominated by solid rocket motors since the 1940s, but cost, rather than performance improvement, has been the paramount consideration. Solid rocket motor technological gains in tactical programs in recent years have been rooted in the technological achievements obtained in strategic programs, where performance is the highest priority.

Although in the past air-breathing propulsion has not been viable for tactical missiles when cost has been the highest priority, it may become a more sensible option in the future. Tactical aircraft are extremely expensive. The conventional warfare environment is becoming increasingly hostile to such aircraft in warfighting scenarios postulated for the 1990s. For aircraft to avoid such hostile environments, particularly during the early days of a large-scale conventional conflict, longer-range and more survivable standoff weapons will be required. That requirement indicates a need for improved propulsion and systems design and integration. Standoff-weapon survivability may be enhanced by higher speeds at lower altitudes and by reduced observables, including radar cross section, smoke, and noise.

The spectrum of propulsion options for tactical missiles is typified in Fig. 1, which shows the variation of specific impulse with flight Mach number for each propulsion concept. Specific impulse is a measure of the efficiency of the propulsion system in converting propellants/fuels to thrust. Each of these propulsion options has its own set of complexities, development schedules, and development, procurement, and life-cycle costs that are of paramount concern in selecting a new tactical missile.

When avionic technologies are improved, propulsion concepts that provide additional capability will be sought. Improved propulsion

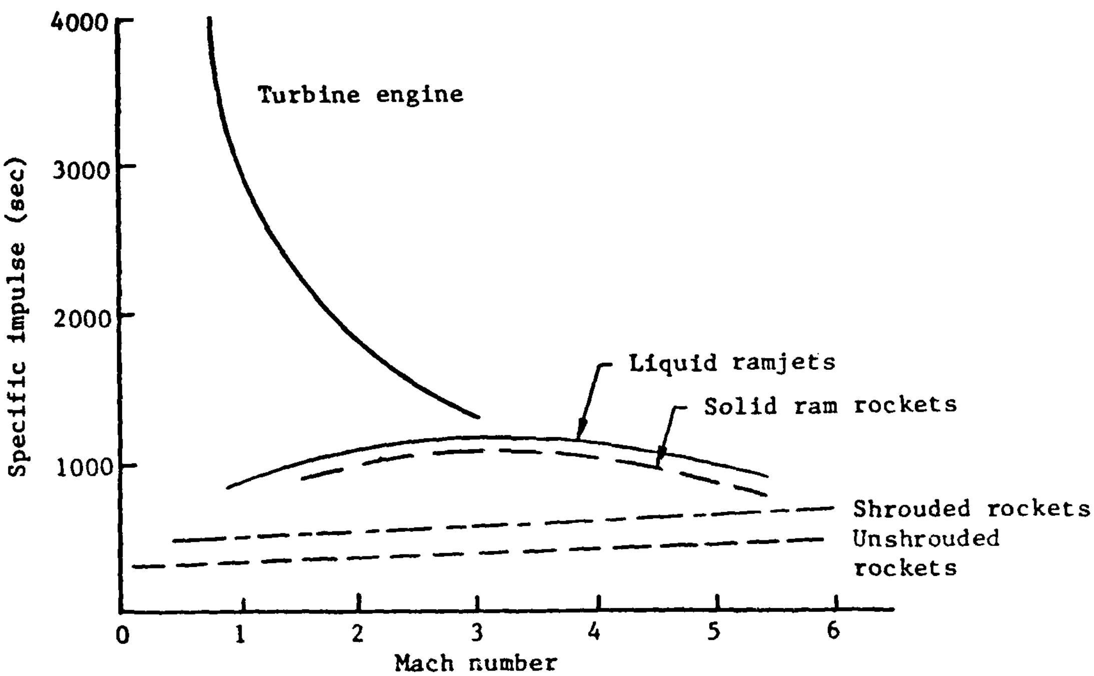

Fig. 1 -- Variation of specific impulse with flight mach number

performance can result in higher penetrating Mach numbers at lower altitudes over longer distances. Depending on ranges of interest, technological improvements in any of the propulsion concepts and missile airframe aerodynamic advances together may result in interesting design options. Thus, the entire spectrum of air-breathing and non-air-breathing propulsion should be considered in deciding requirements for new tactical missiles for the 1990s.

In this section we examine evolutionary technological improvements in propulsion stemming from program achievements of the past several decades. Non-air-breathing and air-breathing propulsion technology trends and programs are addressed.

NON-AIR-BREATHING PROPULSION TECHNOLOGY TRENDS

Solid rockets have been the propulsion method of choice for air-launched tactical missiles. They are inexpensive, simple, reliable, and reasonably safe to handle; they have relatively long shelt life, and they perform modestly. Table 2 presents the technology evolution of strategic and tactical/theater solid rocket propulsion over the past three decades, highlighting propellants, materials, and design improvements.

Solid rocket designs for tactical missiles usually have the shortest development time and the lowest development and production cost for the modest yet adequate performance required to date. Design improvements are reflected in new materials, new propellants, smaller volumes, higher mass fractions, and higher thrust sizes of motors, particularly in the strategic area. Propellant specific impulse has improved about 50 percent from less than 200 seconds in the 1940s to almost 300 seconds today, with similar increases in propellant density from about .045 lb/cu in. to greater than .065 lb/cu in. Thus, solid rocket motor technology has continued to strive for the highest total impulse that can be contained in the allowable motor volume.

The trend for solid tactical motors in the 1980s is away from single-pulse, single-thrust operations toward more complex motors (more

Table 2

TECHNOLOGICAL EVOLUTION OF SOLID ROCKETS

1940s	1950s	1960s	1970s	1980s
Trends				
Cartridge-loaded propellant	Case-bonded propellants			Energy management
Composite propellant (standard 50/50 mix of potassium perchlorate and asphalt binder)	Poured and cured composite propellant (aluminum added)	HTPB and CTPB composites		Computer-aided manufacture and robotics
Double-base propellant (50/50 mix of nitrocellulose binder and nitroglycerine)	Modified double-base propellant (aluminum added)		Composite modified cross-linked double-base propellant	
3500°F combustion temperature			6000° to 6500°F	
Specific impulse: 180 to 205 seconds	225 to 230 seconds	260 seconds		
Propellant density: .045 lb/in^3		.065 lb/in^3		
			Reduced smoke (almost all aluminum removed)	Minimum smoke (aluminum perchlorate removed) Minimum toxicity
Largest motor: 100 lbs of propellant	Diameter: 72 to 84 inches	120 inches	260 inches	
Steel cases	High-strength steel/Al, filament-wound fiberglass, and epoxy composite cases Graphite nozzle insert		Kevlar	Graphite fiber Carbon/carbon nozzles Steel strip wrapping
Mass fraction: 50%	70%		≥90%	
Single-pulse operation	Boost/sustain operation	Dual-pulse operation		Multiple-pulse operation
Burn time: several seconds	Several tens of seconds	60 seconds	120 seconds	180 seconds
		Thrust vector control		Movable nozzle skirts
Companies				
Aerojet Hercules Thiokol	Aerojet Atlantic Research Hercules Phillips Thiokol UTC	Aerojet Atlantic Research Hercules Lockheed Phillips Rocketdyne Thiokol UTC	Aerojet Atlantic Research Hercules Lockheed Rocketdyne Thiokol UTC/CSD	Aerojet Atlantic Research Hercules Thiokol UTC/CSD

complex grain designs) to improve energy management and thus to obtain longer ranges and higher flight velocities for missiles. Boost/sustain thrust levels for single-pulse operation, as well as multiple-pulse motors, however, complicate designs and require additional development time and resources. The effort to minimize observables in tactical operations also complicates the design. The Army favors this development because it will reduce battlefield obscuration and exhaust toxicity.

Solid rocket motors for air-launched missiles at present are designed to wide operational and shelf-life temperature ranges so that they can be stored in a variety of places and operated under a variety of flight conditions. Each improvement of this nature has the effect of reducing the total impulse produced by a motor.

Development and production costs grow as complexity increases. Complex solid rocket motors consume a significantly higher fraction of total missile cost than the simpler designs. In the tactical area, solid rocket motor costs usually represent 5 to 10 percent of total missile cost, with simpler designs tending toward the lower end of that range. Costs of around 10 percent may be similar to costs for expendable air-breathers that could be designed for new, less-expensive missiles of the 1990s.

Liquid rocket propulsion for tactical missile applications has been primarily of the prepackaged type so that missiles may be stored and mounted on aircraft safely without requiring handling of the propellant and oxidizer by ground crews. Only a few tactical air-launched applications have occurred, primarily for Bullpup and a version of Sparrow in the Air Force.[2] Prepackaged liquid rockets have not been used in this role for over a decade.

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[2]Shipboard safety requirements make liquid rocket motors

In sum, the choice has clearly been solid propellant motors for air-to-air and air-to-surface weapons, and they will continue to be used as long as missile cost remains the most important consideration and the performance they provide is satisfactory for the missile mission requirements.

AIR-BREATHING PROPULSION TECHNOLOGY TRENDS

Air-breathing propulsion can provide, in some missile designs, an order-of-magnitude improvement in specific impulse. Air-breathing engines get their oxygen from the atmosphere, while rockets carry their own oxygen. However, air breathers suffer from a longer development time, larger development and procurement costs, and flight path constraints due to inlet requirements. Furthermore, they are considered less reliable than solid motors because of the added complexities in design, accessories, and installation. Finally, they have not exhibited the long shelf life of solid rockets; their rotating parts need to be tested and replaced occasionally.

Air-breathing propulsion for longer-range tactical missions providing air-launched standoff capability lately has attracted renewed interest. Turbojet, turbofan, ducted rocket, and integral rocket ramjet concepts are being studied for use with conventional standoff weapons. Higher performance over a longer burn time is needed for longer range and higher sustained Mach number to provide standoff capability for aircraft platforms and higher survivability to both the missile and the aircraft.

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impractical for use by the Navy. Thus, all missile applications intending to satisfy both Air Force and Navy requirements have used solid rocket motors.

Table 3 presents technology trends for man-rated and non-man-rated turbine engines. Early non-man-rated missile and drone applications used developed, man-rated engines, usually operating at higher combustion and turbine temperatures to achieve more performance at a shorter design life. The J 33 was an early example. The missile or drone engine did not need as long a design life as manned aircraft.

Today, non-man-rated air-breathing engines are being designed and developed for specific strategic and tactical applications, the first tactical application being the Navy Harpoon. Target drones also use air-breathing engines. Design practice is apparently still very similar to that for man-rated engines, however. Furthermore, there does not seem to be a significant design distinction between durability and reliability except in controls and accessories design and packaging.

The primary emphasis in this evolving technology, particularly for man-rated designs, has been on performance. The technology has provided ever higher turbine inlet temperatures and more efficient compressors, combustors, and turbines.

Performance has improved through higher thrust per unit of weight and lower fuel consumption. Turbine inlet temperatures have increased from around 1500 degrees F in the 1940s to over 2500 degrees F in the 1970s. Thrust per unit of weight has increased from slightly over one in the early days to about eight today. These improvements for the most part result from steady improvements in aerodynamics, combustion, materials, and structural design.

Air-breathing propulsion continues to be justified in strategic applications where cost has been secondary to performance requirements.

Table 3

TURBINE ENGINE TECHNOLOGY TRENDS

Early 1940s	Late 1940s	Early 1950s	Late 1950s	Early 1960s	Late 1960s	Early 1970s
Increased thrust Centrifugal to axial compressor Single-design point mission Limited use of high-temperature steels; primarily conventional steels	Augmentation Two-position nozzle Stainless steel, aluminum, conventional steel Higher pressure ratio, dual rotor	High pressure ratio, variable stators Titanium begins to replace aluminum Sustained supersonic flight Samll helicopter engines Reliability/ durability Moderately higher turbine temperature	Cooled turbine Mach 3 Small lightweight engines Commercial turbojet Subsonic turbofan Titanium and superalloy material improvements Transonic compressor	Supersonic turbofan Multidesign point mission Superalloy materials Lightweight design Component improvements Commercial turbofan	small expendable turbojet High-bypass turbofan (mil. & commercial) High-temperature turbine Cooling techniques 3-spool rotor Compatibility/ integration Increasing sophistication of development Commercial technology & requirements becoming as advanced as military	small expendable turbofan engines for missiles High thrust/ weight High component performance High temperature materials Cooling techniques Composite materials Directionally solidified materials Powder metallurgy
Companies						
General Electric Westinghouse	Allison Boeing Curtiss Wright Fairchild General Electric Pratt & Whitney Westinghouse	Allison Boeing Continental Curtiss Wright Fairchild General Electric Lycoming Pratt & Whitney Ranger Westinghouse	Allison Boeing Continental Curtiss Wright Fairchild General Electric Lycoming Pratt & Whitney Williams	Allison Boeing Continental Curtiss Wright Garrett General Electric Lycoming Pratt & Whitney Williams	Allison Continental Garrett General Electric Lycoming Pratt & Whitney Williams	Allison Continental Garrett General Electric Lycoming Pratt & Whitney Williams

SOURCE: Nelson, J. R., *Life-Cycle Analysis of Aircraft Turbine Engines*, The Rand Corporation R-2103-AF, November 1977.

Examples include the turbojet-powered Hound Dog and Quail in the late 1950s and, most recently, the F-107 turbofan engine for the ALCM. The propulsion has been straightforward turbojet and turbofan for both subsonic and supersonic cruise. Table 4 summarizes turbojet/turbofan missile and drone applications.

For high, sustained Mach numbers (Mach 3 or higher), interest has been shown in the integral rocket ramjet. However, only one Air Force program--BOMARC--achieved full production status using ramjet propulsion, and that was over 20 years ago. Table 5 summarizes ramjet technology trends and programs.

The potential advantages of air-breathing propulsion in tactical missiles include extended range and increased survivability through higher delivery Mach number, decreased size, and lower observable signatures. Design consideration is presently being given to observables, with the aim of reducing smoke, lowering radar cross section, and decreasing noise. Also, better energy management of the flight profile will extend range and increase flight Mach number.

The combination of higher speed at lower altitude over longer range and with decreased observables will increase the survivability of the missile. The additional range can help to control attrition by reducing the penetration distance of aircraft platforms. Historically, air-breathing propulsion has paced development in manned aircraft engine applications, and it may well do the same for tactical missiles.[3]

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[3]The turbofan engine in the strategic/theater cruise missile application (ALCM, SLCM, and GLCM) required a decade of advanced engineering and full-scale development. The simpler turbojet engine in the tactical Harpoon missile required much less time but still paced missile development.

Table 4

NON-MAN-RATED TURBOJET AND TURBOFAN MISSILE AND DRONE APPLICATIONS

1950s	1960s	1970s
	Applications	
Larger engines for missiles: versions of man-rated engines; subsonic and supersonic for strategic applications		Designed specifically for non-man-rated applications
Matador Mace J 33 Regulus I J 52 Hound Dog J 57 Snark J 79 Regulus II J 85 Quail		
Smaller engines for drones; subsonic	Cooled turbine; subsonic; high altitude	Smaller engines for missiles and drones; uncooled turbines; subsonic low altitude
J 44 Firebee J 69 Firebee	J 97 Compass Cope J 69/J 100 Firebee	J 69/J 100 Firebee J 400 Chukar J 402 Harpoon, VSST F-107 ALCM/SLCM/GLCM
	Companies Involved	
Allison Fairchild General Electric Pratt & Whitney Ranger Teledyne Westinghouse	General Electric Teledyne Williams	Teledyne Williams

Table 5

RAMJET AND DUCTED ROCKET TECHNOLOGY TRENDS

1940s	1950s	1960s	1970s	1980s
30 in. dia ramjet subsonic P-80 application, primarily conventional materials, limited use of high temp materials	supersonic alum/steel isentropic spike compression inlets, variable geometry inlets, ceramic insulation in combustor BOMARC (2.7M/60K) Only AF ramjet production program Talos only Navy production program Navaho cancelled	boron slurry fuel integral rocket ramjet designs supersonic combustion ramjet high density hydrocarbon fuel complex thermodynamic cycles Mach 5-8 speed regime nuclear ramjet LASRM - Test only Mach 2.5/SL	integral rocket ramjet tests for tactical missiles, inconel and titanium materials ASALM-PTV - Test only ASALM-TIP - Test only solid fuel ramjet *solid ducted rocket* Firebrand development	electronic fuel control first ramjet engine qualified in 20 years for Firebrand (since cancelled) variable flow ducted rocket ASALM carbon/carbon combustion chamber/ exit nozzle
Curtiss Wright General Electric Marquardt	Curtiss Wright General Electric Marquardt UTC	Curtiss Wright General Electric Marquardt UTC	Marquardt UTC	Marquardt UTC

The disadvantages of air-breathing propulsion remain the high cost of development and procurement and longer development time. Air-breathing engines are more complex and less reliable than simple solid rockets, given that complex fuel controls (to optimize the thermodynamic cycle at several flight conditions), possible variable geometry (inlet and exhaust), relight ignition systems, and recirculating lubrication systems are usually used in these engines.

These items require much additional engineering, testing, time, and money. In addition, air-breathers appear to have a shorter shelf life, requiring more frequent checkout and more extensive operations and maintenance support costs. Their value to tactical missile applications must therefore be examined carefully.

III. TECHNOLOGY TRENDING AND RISK ANALYSIS OF PROPULSION SYSTEMS

INTRODUCTION

In its broadest context, this study deals with ordnance at the weapon system level, where the weapon system is composed of discrete major subsystems, including airframe, propulsion, avionics, and warhead. The research seeks to develop a quantitative approach to risk assessment.

To achieve this objective, we devised a probability measure that may be applied to the technological content of a subsystem--and to all subsystems in a similar way--and then integrated into the total weapon system. This quantitative approach involves two steps: (1) time trending using regression analysis of performance characteristics, and (2) risk assessing to learn whether a program was advanced or conservative relative to the state of the art, using a probability measure through application of a logit regression procedure.

This section analyzes and evaluates this exploratory investigation of risk. For the study, we selected an important subsystem--propulsion for aircraft and tactical missiles--and developed and applied the method through review and survey of the performance spectrum of propulsion, characterizing the technology of the various propulsion types, collecting the relevant program data from the military services and manufacturers, deriving state-of-the-art trend models, specifying a risk measure by means of a consistent decision rule, deriving a risk model, and evaluating the results.

Particular propulsion programs are examined to verify that results seem sensible relative to historical evidence. Propulsion was selected as the initial subsystem partly because of previous Rand experience in this area and partly because of the apparent existence of a significantly large data base for analysis.

STATE-OF-THE-ART TRENDING

About a decade ago, Rand developed a method to measure the technological trend over time for particular military hardware subsystems. The technique was applied to aircraft turbine engine state of the art and life-cycle analysis and later to fighter aircraft state of the art.[1]

For the engine application, a specific set of engine performance characteristics obtained at the 150-hour model qualification test (MQT) date served as a proxy measure of technological advance. An equation obtained by regression analysis was used to predict the MQT date for a new engine as a function of engine thrust, weight, turbine inlet temperature, specific fuel consumption, and a term representing the product of the maximum dynamic pressure of the engine's operating envelope and its pressure ratio.

This method is extended here to represent the state of the art for different classes of missile propulsion systems to aid in predicting the technological risk involved in the development and production of such

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[1]See Arthur J. Alexander and J. R. Nelson, *Measuring Technological Change: Aircraft Turbine Engines*, The Rand Corporation, R-1017-ARPA/PR, June 1972; J. R. Nelson, *Life-Cycle Analysis of Aircraft Turbine Engines*, The Rand Corporation, R-2103-AF, November 1977; and William L. Stanley and Michael D. Miller, *Measuring Technological Change in Jet Fighter Aircraft*, The Rand Corporation, R-2249-AF, September 1979.

propulsion systems designed for U.S. air-to-surface munitions in the 1990s.

The trend analysis compares the actual date (converted into an elapsed time measured from some reference date) on which an engine achieves its 150-hour MQT with the date predicted by an equation obtained by regression analysis of several characteristic engine technology parameters. The 26 engines in the original data base are listed in Table 6. Figure 2 displays the calculated and actual MQT dates for those engines.

The trend equation for these engines was found to be

$$\mathrm{MQTQTR} = \underset{(-5.8)}{-856.4} + \underset{(3.1)}{110.1} \ln \mathrm{TEMP} + \underset{(5.1)}{11.4} \ln \mathrm{TOTPRS} - \underset{(-2.8)}{26.1} \ln \mathrm{WGT}$$

$$\underset{(-2.8)}{-16.0} \ln \mathrm{SFCMIL} + \underset{(2.8)}{18.4} \ln \mathrm{THRMAX},$$

where the numbers in parentheses are t-statistics for the regression coefficients and the engine parameters are defined as follows:

MQTQTR = time of arrival of an engine at its 150-hour model qualification test (calendar quarters measured from October 1942)

TEMP = maximum turbine inlet temperature (Rankine)

TOTPRS = product of the maximum dynamic pressure in flight envelope and the pressure ratio (lb/sq ft)

WGT = engine weight at configuration of interest (lb)

SFCMIL = specific fuel consumption at military thrust, sea-level static (lb/hr/lb thrust)

THRMAX = maximum thrust (with afterburner if afterburner configuration), sea-level static (lb)

Table 6

DATES OF DEVELOPMENT INITIATION FOR SELECTED U.S. AIRCRAFT TURBINE ENGINES

Early 1940s	Late 1940s	Early 1950s	Late 1950s	Late 1960s
J 30 W	J 40 W	J 52 PW	J 58 PW	TF 34 GE
J 31 GE	J 42 PW	J 65 CW	J 60 PW	TF 39 GE
J 33 GE/A	J 46 W	J 69 C	J 85 GE	TF 41 A
J 34 W	J 47 GE	J 75 PW	TF 30 PW	
J 35 GE/A	J 48 PW	J 79 GE	TF 33 PW	
	J 57 PW			
	J 71 A			
	J 73 GE			

NOTE: W = Westinghouse; GE = General Electric; A = Allison; PW = Pratt & Whitney; C = Continental; CW = Curtiss Wright.

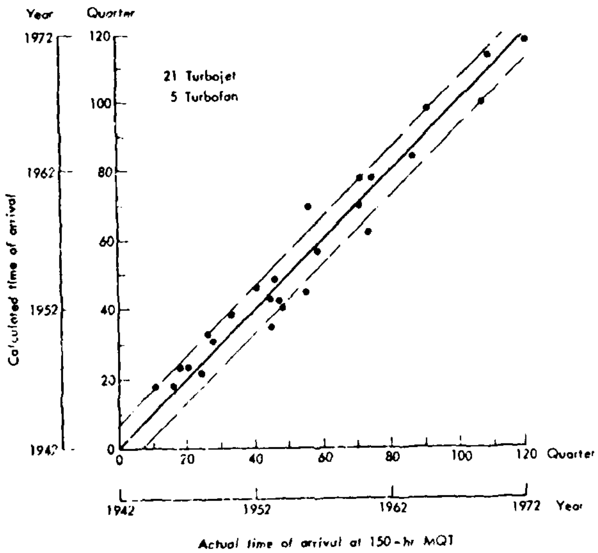

Fig. 2--Military aircraft turbine engine trend

In Fig. 2, the predicted MQT date for each engine, calculated using the regression equation above, is plotted on the vertical axis. The engine's actual time of arrival is measured along the horizontal axis.

An engine whose TOA, calculated using the regression equation, agrees with its actual time of arrival, produces a data point falling on the 45-degree line. Data points falling above the 45-degree line represent advanced engines in the sense that they arrived at their MQT earlier than predicted by the industry trend. Data points falling below the 45-degree line represent conservative engines in the sense that they arrived later than expected relative to the industry norm. The dashed lines in Fig. 2 represent one standard error in the trend line.

Two assumptions underlie this trend depiction: (1) the state of the art of manned aircraft engine technology is evolutionary and future aircraft engine programs depend on past industry experiences and (2) investments in engine-related research will continue at a reasonable pace with the dominant firms remaining active and in competition.

COMBINING MAN-RATED AND NON-MAN-RATED DATA

Owing to the limited data available for non-man-rated engines, we have combined the data for all military engines listed in Table 7.[2] Three engines--the J 33, J 57, and J 79--were removed from the non-man-rated data base because they had previously been developed as man-rated engines. Three man-rated engines--the F-100, F-101, and F-404--were added to the 26 previously discussed.

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[2]Data for these initial runs were obtained from the Air Force; more detailed data were provided by the manufacturers.

We estimated the trend as a function of several technology-related variables. These variables are (1) a dummy (UMDUM) to differentiate between man-rated (UMDUM = 0) and non-man-rated (UMDUM = 1) engines, (2) the engine thrust-to-weight ratio (THRMAX/WGT), and (3) maximum turbine

Table 7

AIRCRAFT TURBINE ENGINE DEVELOPMENTS

1940s	1950s	1960s	1970s	1980s
Man-Rated				
J 30	J 40	J 52[a]	TF 34	
J 31	J 46	J 58	F-100	
J 33	J 48	J 60	F-101	
J 34	J 57	J 85[a]	F-404	
J 35	J 65	TF 30		
J 42	J 69[a]	TF 33		
J 47	J 71	TF 39		
	J 73	TF 41		
	J 75			
	J 79			
Non-Man-Rated				
J 33(b)	J 44	J 97	J 402	F-107
	J 52	J 100		
	J 57[b]	J 400		
	J 69			
	J 79[b]			
	J 85			

[a]Originally a non-man-rated development at a different performance level; both versions were used in the final combined data base.

[b]Originally a man-rated development used in a missile at the same performance level; used only as a man-rated engine in the final combined data base.

inlet temperature (TEMP) in Rankine.

The resulting regression equation and relevant statistics for the qualification test date for the 29 man-rated and 9 non-man-rated examples are as follows:

$$\underset{}{QTQTR} = \underset{(-4.9)}{-102.5} + \underset{(3.8)}{8.36}\,(THRMAX/WGT) + \underset{(5.1)}{0.059}\,(TEMP) + \underset{(3.3)}{22.5}\,UMDUM$$

$$\begin{aligned} \text{R-square} &= .82 \\ F &= 52.5 \\ SE &= 17.1 \end{aligned}$$

The numbers in parentheses are t-statistics for the regression coefficients.

The data are plotted in Fig. 3. Again, the coefficients have intuitively correct signs. The equation obtained by combining man-rated and non-man-rated aircraft turbine engines includes thrust/weight and turbine temperature as important variables.

Because most non-man-rated engines use uncooled turbines, today they appear technologically conservative in any technology comparison with man-rated engines. The value of the coefficient of UMDUM indicates that, on average, the non-man-rated engines show up 5+ years later than man-rated engines.

Today, the turbine inlet temperatures of non-man-rated engines such as the J 402 and F-107 are 600 to 700 degrees F lower than those of the current man-rated engines that use cooled turbine blades and vanes. However, turbine materials used in non-man-rated engines are closer to the state of the art of allowable metal temperatures.

The equation should not imply that acquiring a non-man-rated engine is a simple task. A reasonable development period and a concerted

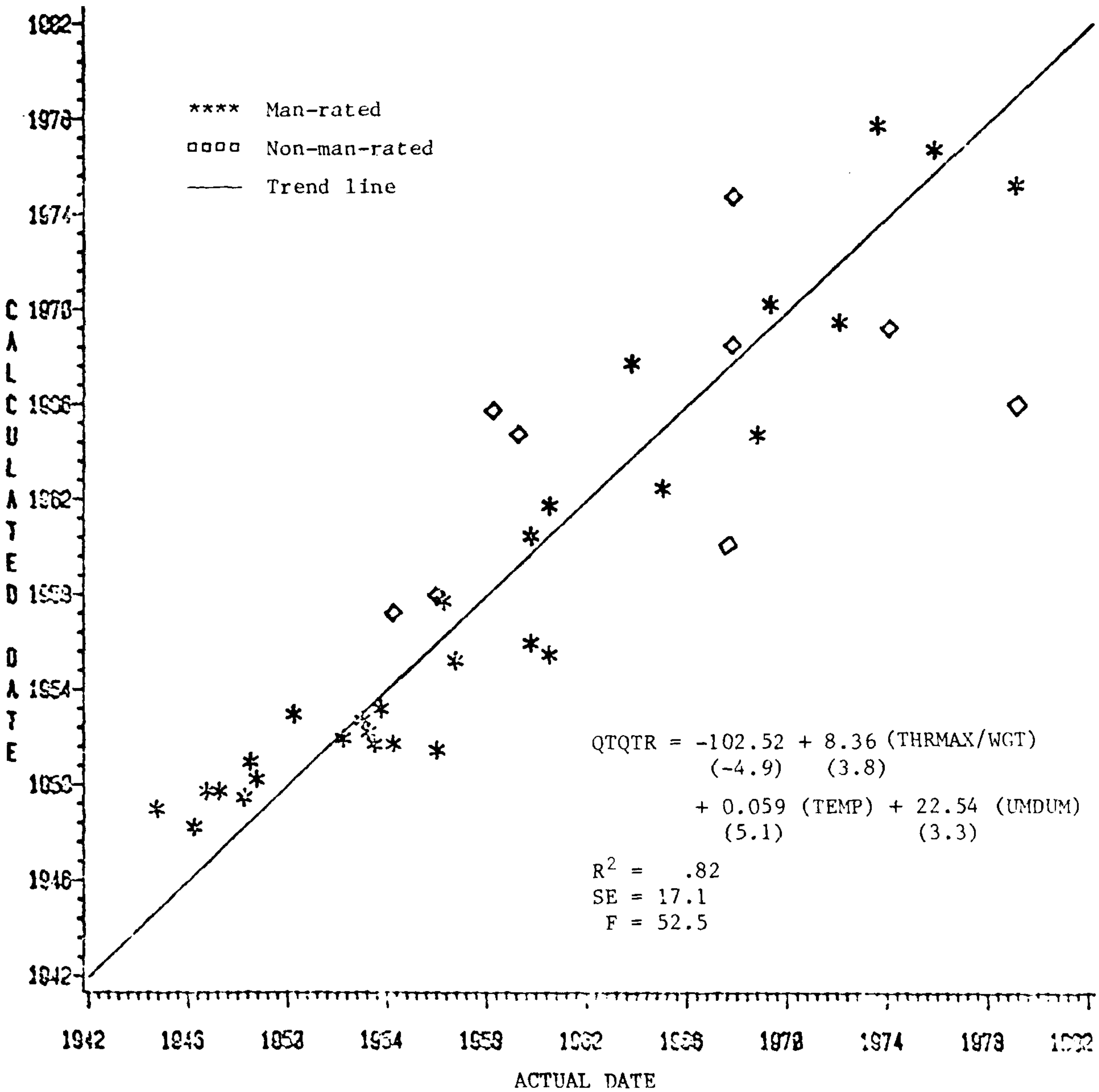

Fig. 3--Model qualification date for 29 man-rated and 9 non-man-rated military turbine engines

development effort are still needed to obtain a non-man-rated engine. But it can be obtained in less time and at less cost than current large man-rated engines that use cooled turbine technology and require extensive development and testing and continuing product improvement.

Among the non-man-rated engines, the J 85 and J 97 were quite advanced for their time. The F-107, which has taken about ten years to develop, appears quite conservative. For an engine that passed its MQT in 1980, the lack of an air-cooled turbine puts it about 600 to 700 degrees F behind present technology. The J 85 and J 97 were advanced engines for non-man-rated applications at the time they were developed, the J 85 having a very high thrust-to-weight ratio and the J 97 being the only n air-cooled turbine in the non-man-rated data base. The results of this initial combining of man-rated and non-man-rated air-breathing engines to obtain a state-of-the-art evolutionary trend are encouraging.

DETERMINING THE TREND IN SOLID ROCKETS

This subsection discusses non-man-rated solid rocket motor propulsion; data on non-man-rated air-breathing engines will be combined with these data in the following subsection. Solid rocket motors have played a significant role in the propulsion of both air- and ground-launched missiles. We present here an initial effort to develop a trend model for solid rocket engines. The results are promising, but at the same time we feel that considerable improvement is possible.

The 28 motors included in the model are shown in Table 8. Performance data for these motors include thrust, weight, specific

impulse, total impulse, and motor design variables such as boost/ sustain and operating and storage temperature ranges.[3]

Table 8

SOLID ROCKET MOTOR DEVELOPMENTS

1950s	1960s	1970s
Falcon	Terrier	Maverick
A/C booster I	Pershing	Sparrow (MK58)
Sparrow (MK6)	Sparrow (MK38)	
Sidewinder (NOTS)	Roadrunner	
Lacrosse	Phoenix	
Matador booster	AIM-47	
Mace booster	A/C booster II	
Regulus booster	Bullpup B	
Talos booster	Sidewinder (MK36)	
Tartar	SRAM	
	Standard ARM	
	Genie	
	AIM-26	
	SUROC	
	JATO	
	Bomarc booster	

[3]Data for initial analyses were obtained from the Air Force; more detailed data were provided by the manufacturers.

The following model obtained the best estimates of the qualification test date:

```
QTQTR = 34.0 + 4.8 (ITM/VT) + 12.2 TEMPDUM + 20.2 BOSUDUM
        (3.5)  (3.4)          (2.5)          (2.7)
```

R-square = .67
F = 16.1
SE = 12.4

where ITM = total impulse for mission (lb-sec)

VT = total volume of engine and fuel (cu in)

TEMPDUM = a dummy variable = 0 for temperature range[4] less than 180 degrees F

= 1 for temperature range equal to or greater than 180 degrees F

BOSDUM = a dummy variable = 0 for no boost/sustain mode of operation

= 1 for boost/sustain mode of operation.

The estimated qualification date of these motors using the variables is plotted against actual date in Fig. 4. Total impulse per volume, a temperature dummy, and a boost/sustain dummy were used to obtain a reasonable model.

All of the variables have the appropriate signs for the coefficients. Increasing total impulse per volume delays the expected qualification date. Designing a motor for a wide temperature range or one with boost/sustain capability also extends the time to the expected qualification date. Falcon, Sparrow, and Sidewinder motors are among influential data points that appear to be advanced for the time they were qualified, while Maverick was conservative.

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[4]The range of ambient temperatures over which the missile must operate.

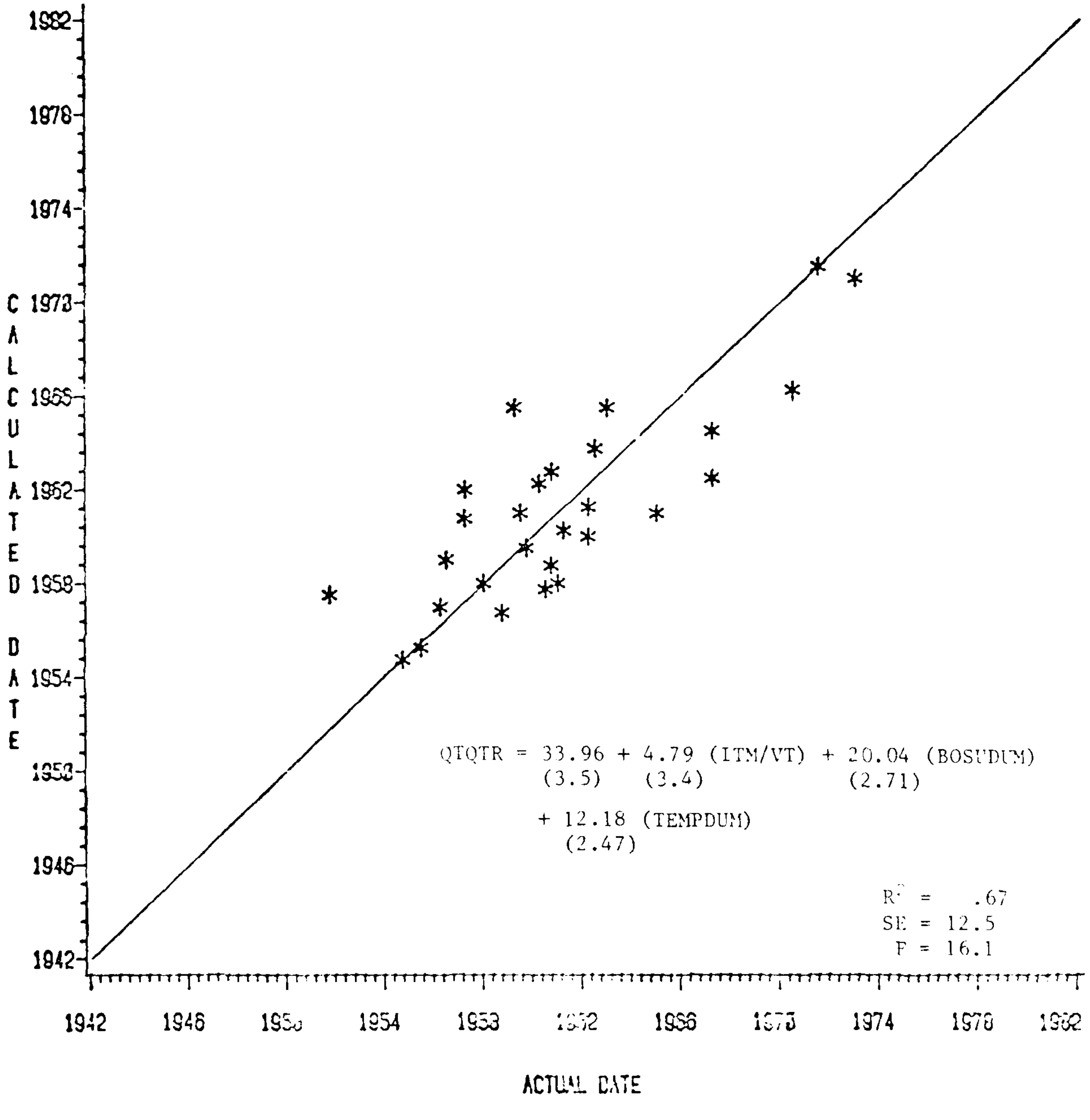

Fig. 4--Model qualification date for 28 solid fuel military rocket motors

COMBINING SOLID ROCKETS AND NON-MAN-RATED AIR-BREATHING ENGINES

The 28 solid rockets were combined with the previous 9 non-man-rated air-breathing engines to otain the following equation:

$$\begin{array}{llllll} QTQTR = & -51.6 & + 2.1 \ln (ITM/VT) & + 25.2\ BOSUDUM & + 14.2\ TEMPDUM & - 93.7\ ABDUM \\ & (10.8) & (5.4) & (2.9) & (2.3) & (-5.6) \end{array}$$

$$\begin{aligned} R\text{-square} &= .65 \\ F &= 14.8 \\ SE &= 15.5 \end{aligned}$$

where ABDUM = a dummy variable = 0 for non-air-breathing motors

= 1 for air-breathing engines

Here, again, total impulse per volume is a strong explainer of the total data base. The boost/sustain dummy also enters as an additional explainer of the state-of-the-art trend. The temperature range is significant in this model, but the air-breathing dummy, which separates the 28 solid rockets from the 9 air-breathers, is highly significant. This dummy really is accounting for air-breathers' not having to carry their own oxidizer, whereas solid rockets must. Thus, air-breathers do not require as large a volume for the total impulse that they can deliver. However, they are more costly and complex.

The estimated and actual qualification dates are plotted in Fig. 5. Some of the same programs that were influential in previous models show up again. This consistency is encouraging, and it provides insight for investigating certain programs in more detail to obtain a better understanding of data inputs and of this technique.

These state-of-the-art time trends for technology do not display all of the factors that would be considered in selecting an air-breathing engine or solid rocket motor in a new missile application.

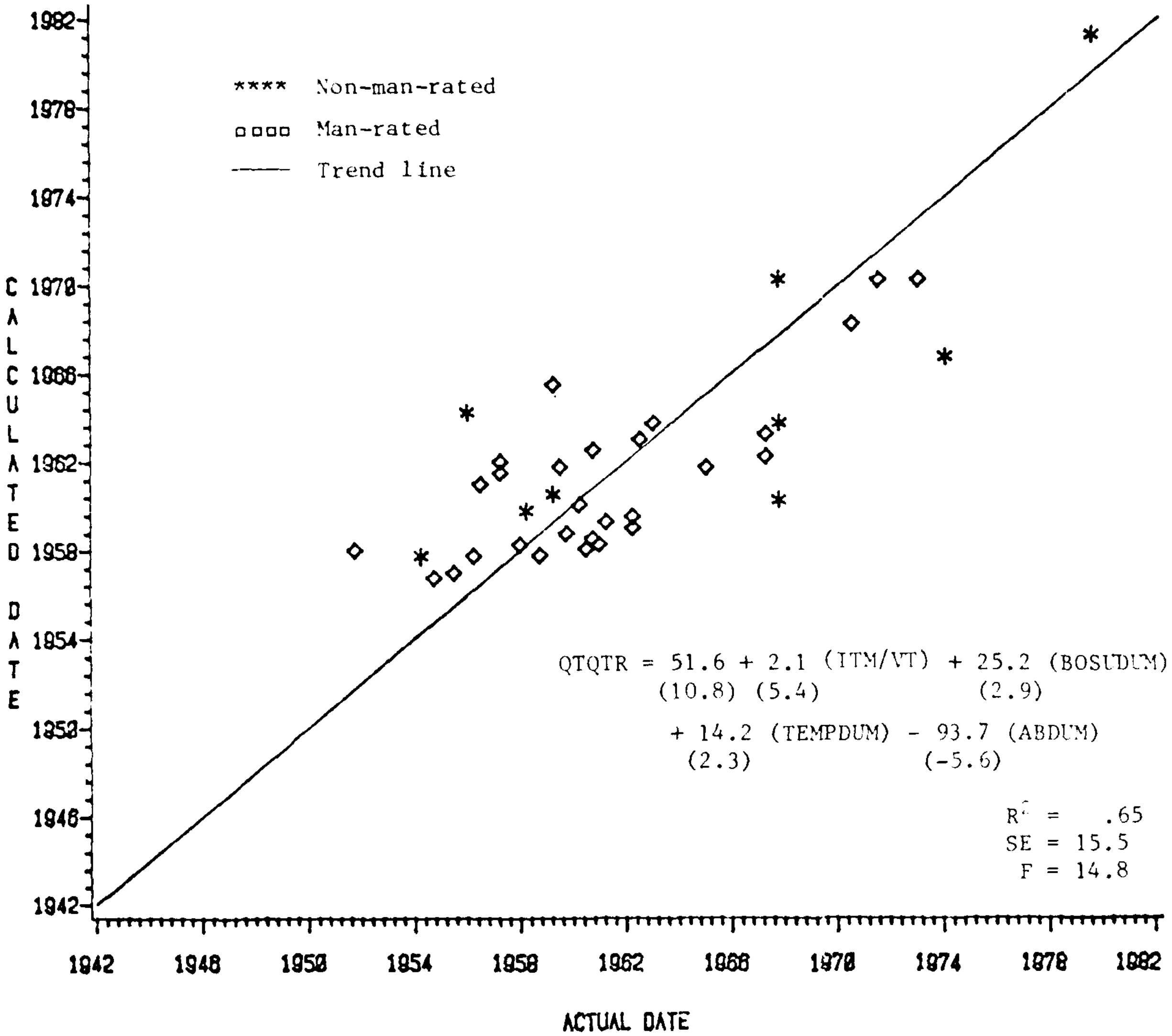

Fig. 5--Model qualification date for 28 solid rockets and 9 non-man-rated turbine engines

For instance, development time and cost and production unit cost are critical considerations; they must be considered in future analyses.

DETERMINING TECHNOLOGICAL RISK IN PROPULSION SYSTEM DEVELOPMENT

As we have seen, the technical characteristics of a specific engine may vary significantly from the industry trend. A measure of risk is involved in the engine development, production, and operational life cycle. We therefore need to develop a procedure for estimating the technical risk associated with a particular engine development program.

In this application, we define risk as the probability of not achieving the specified performance at the specified date. This implies the use of a dichotomous variable, that is, one that will indicate whether or not the specified performance and schedule goals are achieved. A logistic model would be appropriate for this application.[5]

To analyze the risk associated with engine development programs, we developed the parameters for a logistic model using conventional regression procedures to estimate how the probability of early or late arrival depends on certain engine performance parameters. We begin this risk analysis by using the trend analysis for the 38 air-breathing engines, including the man-rated engines that passed a 150-hour MQT and the non-man-rated engines that passed a 10- to 15-hour qualification test.

Using the dichotomy of early and late arrival from the TOA analysis, let Y be an indicator variable having the value of 1 for the

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[5]See Carl Morris and John E. Rolph, Introduction to Data Analysis and Statistical Inference, The Rand Corporation, P-5819, June 1978.

engines that were below the 45-degree line in the trend analysis (i.e., engines judged to be technologically conservative) and 0 for those that fell above the line (technologically advanced). Let X denote the vector of performance characteristics:[6]

$$X = \Delta THRMAX/WGT,\ \Delta TEMP,\ UMDUM$$

We assume that the conditional probability of late arrival, given X = x, is given by

$$P(Y = 1 | X = x) = 1/[1 + \exp -(a + b'x)],$$

where a and $b' = (b_1, b_2, b_3)$ are parameters to be estimated.

Fitting the model by maximum likelihood yields estimates for the logistic regression coefficients, shown in Table 9. Table 10 displays the estimated probabilities for each of the engines in this sample. That is, for each engine the values of the three independent parameters were put into the model, yielding for each engine an individual calculation of the probability that that engine could accurately be described as conservative in terms of performance objectives (equivalent to expecting its arrival later than predicted by a TOA trend analysis).

Had these probabilities been available before the engines were developed, they could have been used to predict whether a given engine would be advanced or conservative in its technological content. The data in the table may be analyzed using individual probabilities for each program or by ranking the various programs.

Table 9 also provides the model statistics and a matrix of "hits" and "misses" for both late and early estimates and actual outcomes. A program whose probability was calculated to be 0.5 or greater is

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[6] The Δ values were determined by performing a linear fit to the variation of each separate parameter over time and then measuring the deviation of a particular data point from that average trend line.

Table 9

MODEL OF TECHNOLOGICAL RISK BASED ON PERFORMANCE CHARACTERISTICS: AIR-BREATHING ENGINES

Model chi-square = 27.51 with 3 DF
D = 0.447
-2 log L = 24.75
P = 0.0000

Variable	Beta	Standard Error	Chi Square	P	D
Intercept	0.38224121	0.56765942	0.45	0.5007	
ΔTHRMAX/WGT	-2.77876274	1.15302348	5.81	0.0160	0.146
ΔTEMP	-0.01543835	0.00631897	5.97	0.0146	0.149
UMDUM	-5.21543065	2.27092575	5.27	0.0216	0.134

Classification Table

	PREDICTED		
TRUE	Advanced	Conservative	Total
Advanced	18	3	21
Conservative	2	15	17
Total	20	18	38

Sensitivity	88.2%
Specificity	85.7%
Correct	86.8%
False positive rate	16.7%
False negative rate	10.0%
Predictive accuracy coefficient	0.530

Table 10

ESTIMATED PROBABILITIES OF ENGINES IN THE DATA SAMPLE

Type[a]	ΔTHRMAX/WGT	ΔTEMP	UMDUM	PL	Probability[b]
J01	0.1104	-17.62	0	0	0.5860
J02	-0.0502	125.02	0	0	0.1965
J03	-0.2006	98.16	0	0	0.3599
J04	0.1597	-23.69	0	0	0.5755
J05	-0.5785	133.95	0	0	0.4805
J06	-0.1970	-61.63	0	1	0.8677
J07	0.4202	-79.48	0	0	0.6086
J08	0.0711	-54.52	0	1	0.7362
J09	-0.5505	148.41	0	0	0.4063
J10	0.2840	68.66	0	0	0.1874
J11	-0.2120	-192.74	0	1	0.9811
J12	-0.6839	41.80	0	1	0.8372
J13	0.1411	414.87	0	0	0.0016
J14	2.2789	-171.41	0	0	0.0354
J15	-0.7154	-23.73	0	1	0.9392
J16	-0.9025	-139.81	0	1	0.9936
J17	-0.9789	99.16	0	1	0.8280
J18	-1.0637	-15.05	0	1	0.9726
J19	0.1688	-86.13	0	1	0.7761
J20	0.7923	28.09	0	0	0.0951
J21	2.3960	-152.74	0	0	0.0195
F01	-0.2463	49.33	0	1	0.5756
F02	0.1161	-171.41	0	1	0.9374
F03	0.4021	80.33	0	1	0.1218
F04	-0.1170	338.51	0	0	0.0108
F05	-1.0621	132.72	0	1	0.7832
F06	1.5308	402.69	0	0	0.0000
F07	0.4597	373.72	0	0	0.0013
F08	0.2037	141.33	0	1	0.0858
A02	-0.4459	-115.05	1	0	0.1397
A03	-0.4345	142.80	1	0	0.0029
A05	-0.4821	-139.81	1	0	0.2083
A07	2.9112	-218.77	1	0	0.0001
A08	0.4709	251.15	1	0	0.0000
A09	0.8041	-208.85	1	0	0.0210
A10	-2.5238	-298.85	1	1	0.9989
A11	0.1624	-376.53	1	1	0.6292
A12	-2.4386	-522.89	1	1	1.0000

[a]Notes to Table 10 appear at the top of p. 36.

Notes to Table 10

[a]Specific engines are not identified because of proprietary and classification restrictions. The prefix "J" denotes manned turbojet engines; "F," manned turbofan engines; "A," unmanned turbojet or turbofan engines; and "S," solid rocket motors.

[b]The probability shown here is the probability that the combination of performance characteristics for that engine are on the conservative side of the long-term industry trend.

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assigned to the "conservative" category. A program whose probability was calculated to be less than 0.5 is assigned to the "advanced" category. These outcomes were then compared with the results of the TOA analysis shown on Fig. 5, above (characterized as the "true" value in this comparison).

The matrix indicates that 33 engines would have been classified correctly (15 late and 18 early) and 5 would have been misclassified. The model chi-square in this case is 27.5 with 3 degrees of freedom. As seen in Table 9, the percentage of late engines predicted by the model to be late is 88. The percentage of early engines predicted to be early is 86. Overall, 87 percent of the engines are correctly assigned.

Similar good results were obtained for the solid rocket motors. Using the same logisic model to analyze the solid rocket motor data, we obtained the corresponding risk estimation model. The model results are presented in Table 11.

The performance characteristics are the difference in total impulse per volume (ΔITM/VT) for the particular motor design relative to the trend, and the boost/sustain and temperature dummies. These

Table 11

MODEL OF TECHNOLOGICAL RISK BASED ON PERFORMANCE CHARACTERISTICS: SOLID ROCKET MOTORS

Model chi-square = 10.14 with 3 DF
D = 0.297
-2 log L = 27.38
P = 0.0174

Variable	Beta	Standard Error	Chi-Square	P	D
Intercept	1.29034159	0.71824124	3.23	0.0724	
ΔITM/VT	-1.00030418	0.46648882	4.60	0.0320	0.161
TEMPDUM	1.94614662	1.03701247	3.52	0.0606	0.128
BOSUDUM	1.76036451	1.44635363	1.48	0.2236	0.058

Classification Table

	PREDICTED		
TRUE	Advanced	Conservative	Total
Advanced	7	4	11
Conservative	2	15	17
Total	9	19	28

Sensitivity	88.2
Specificity	63.6
Correct	78.6
False positive rate	21.1
False negative rate	22.2
Predictive accuracy coefficient	0.295

characteristics were shown to be important explainers of the time trend of solid rocket motors presented above. The estimated probabilities of being in the "conservative" population is shown in Table 12 for each of the solid rocket motors in the sample. This model, like the air-breathing data model, appears to capture the technological risk of solid rocket motors satisfactorily.

Table 12

ESTIMATED PROBABILITIES OF SOLID ROCKET MOTORS

Type	BOSUDUM	TEMPDUM	ΔITM/VT	PL	Probability
S01	0	0	0.5977	1	0.6665
S04	0	0	-0.9112	1	0.9004
S06	0	1	0.9769	0	0.1634
S07	0	0	-0.9473	1	0.9036
S08	0	1	0.8268	0	0.1850
S09	0	1	0.4798	1	0.2431
S10	0	0	0.7023	1	0.6429
S11	0	1	2.3905	0	0.0453
S12	0	0	-0.5901	0	0.8677
S13	1	1	-2.9829	1	0.9835
S14	1	1	1.0332	1	0.5177
S16	0	1	-1.2711	1	0.6492
S18	0	1	-1.8066	1	0.7597
S20	0	0	-1.7361	1	0.9538
S21	0	0	-0.0343	1	0.7900
S22	0	0	-1.2549	1	0.9273
S23	0	0	-2.0512	1	0.9658
S24	0	0	2.8903	0	0.1679
S25	0	0	-0.2293	1	0.8205
S26	0	0	1.0095	1	0.5697
S27	1	0	1.7118	0	0.7922
S28	1	1	0.2259	1	0.7065
S29	0	0	0.9699	0	0.5794
S30	0	1	-0.1732	0	0.3816
S31	0	1	0.5996	0	0.2217
S32	0	1	-1.3257	0	0.6616
S33	0	0	1.4808	1	0.4524
S34	0	1	-0.5814	0	0.4814

A combination of solid rocket motors and non-man-rated air breathing engines was also investigated. The model is shown in Table 13 and the program probabilities in Table 14. This model is not as statistically significant as the previous two, in which the air-breathing and non-air-breathing data were treated separately.

Table 13

MODEL OF TECHNOLOGICAL RISK BASED ON PERFORMANCE CHARACTERISTICS: SOLID ROCKET MOTORS AND NON-MAN-RATED AIR-BREATHING ENGINES

Model chi-square = 1.51 with 2 DF
D = 0.042
-2 log L = 45.12
P = 0.4708

Variable	Beta	Standard Error	Chi-Square	P	D
Intercept	0.91839942	0.41877925	4.81	0.0283	
ΔITM/VT	-0.07269683	0.08691371	0.70	0.4029	0.020
ABDUM	-0.67874383	0.81425130	0.69	0.4045	0.020

Classification Table

	PREDICTED		
TRUE	Advanced	Conservative	Total
Advanced	1	11	12
Conservative	2	23	25
Total	3	34	37

Sensitivity	92.0%
Specificity	8.3%
Correct	64.9%
False positive rate	32.4%
False negative rate	66.7%
Predictive accuracy coefficient	0.120

Table 14

ESTIMATED PROBABILITIES OF SOLID ROCKET MOTORS
AND NON-MAN-RATED AIR-BREATHING ENGINES

Type	ABDUM	ΔITM/VT	PL	Probability
A02	1	0.155	1	0.5568
A03	1	-1.321	0	0.5831
A05	1	10.171	1	0.3776
A07	1	-1.517	0	0.5866
A08	1	6.706	0	0.4384
A09	1	-5.793	0	0.6594
A10	1	-12.778	1	0.7629
A11	1	-8.094	1	0.6960
A12	1	12.472	1	0.3392
S01	0	0.598	1	0.7058
S04	0	-0.911	1	0.7280
S06	0	0.977	0	0.7000
S07	0	-0.947	1	0.7285
S08	0	0.827	1	0.7023
S09	0	0.480	1	0.7076
S10	0	0.702	1	0.7042
S11	0	2.391	0	0.6780
S12	0	-0.590	1	0.7234
S13	0	-2.983	1	0.7568
S14	0	1.033	0	0.6992
S16	0	-1.271	1	0.7332
S18	0	-1.807	1	0.7407
S20	0	-1.736	1	0.7397
S21	0	-0.034	1	0.7152
S22	0	-1.255	1	0.7329
S23	0	-2.051	1	0.7441
S24	0	2.890	0	0.6700
S25	0	-0.229	1	0.7181
S26	0	1.009	0	0.6995
S27	0	1.712	0	0.6887
S28	0	0.226	1	0.7114
S29	0	0.970	0	0.7001
S30	0	-0.173	1	0.7173
S31	0	0.600	1	0.7057
S32	0	-1.326	1	0.7340
S33	0	1.481	0	0.6923
S34	0	-0.581	1	0.7233

EVALUATING THE RESULTS

The logistic model and the individual predictions may be used to gain insight into particular programs. Provided such insights are reasonable with regard to the historical evidence, they may contribute to new development programs by answering questions from past programs, for example: Why was the Maverick solid motor program successful? Why was the SRAM motor late? Why has the F-100 aircraft turbine engine program had operational difficulties?

Using the logistic model, we can calculate not only the probability associated with a milestone date, but also changes in that probability over time. Such calculations are illustrated in Fig. 6. The Maverick motor probability was calculated to be above .95 during its entire development period. Even at the beginning, it had a very high probability. Thus, this motor development may be viewed as a conservative technological effort. Historical evidence indicates this to be the case. The Maverick motor used a propellant developed for the Falcon missile more than ten years earlier.

The SRAM motor development, in contrast, was initiated during a time when the probability was changing quite rapidly. At the beginning of the SRAM development, the probability was quite low. The motor did not achieve its original planned qualification test, slipping by two years. The motor was considered advanced technology for its time. In fact, Lockheed Propulsion Company, the developer, under a total package procurement contact, brought a successful suit against the government to obtain additional money on the grounds that the requirement was too demanding at the outset of the program.

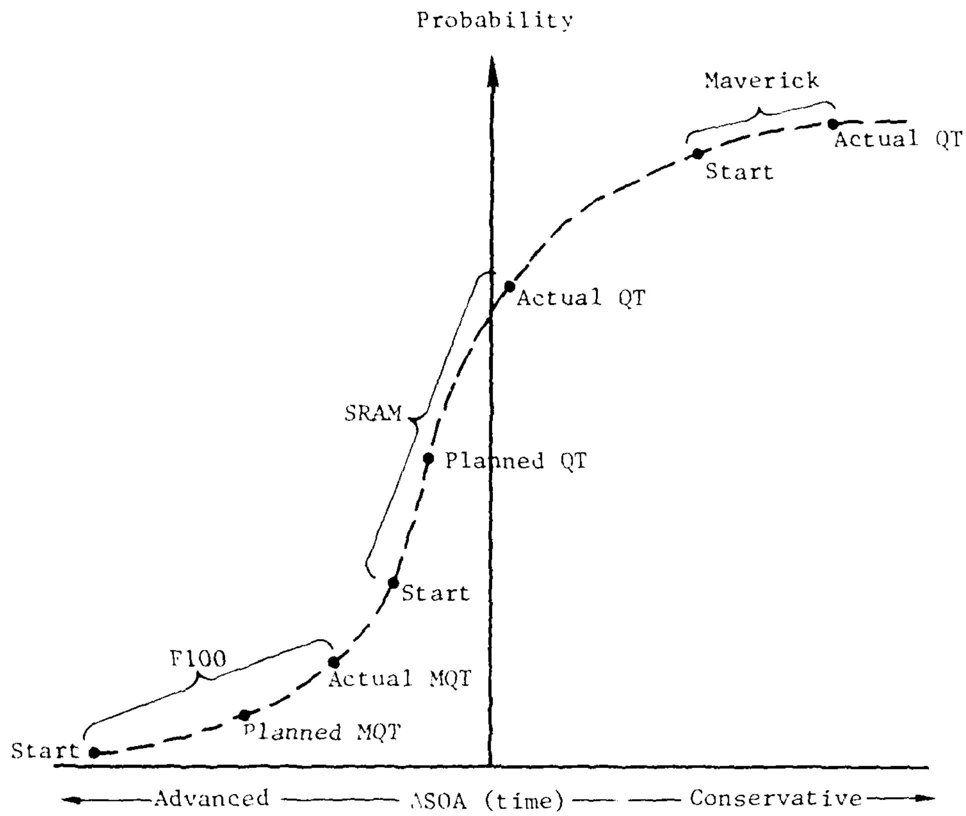

Fig. 6 -- Examples of development programs

The F-100 engine was acknowledged to be highly advanced for its time. In fact, it had the lowest calculated probability of all engines in the air-breathing data base. Its performance goals were achieved, although late. Even for the date at which they were achieved, the probability was very low.

Perhaps the F-100 experience indicates something about the nature of the development testing and qualifying of such engines for operational use. Even now, eight years later, the F-100 would not be considered a mature technology. It continues to have reliability and endurance problems in operational use, despite many years of improvements.

This risk assessment technique is not intended to indicate that an advanced technology cannot be achieved on schedule. It implies only that if the probability is low, the program may carry significant risk with regard to schedule slippage, cost growth, and reliability and endurance problems in operational use.

If a decisionmaker understands the risk in undertaking the development program and still feels that a particular subsystem is necessary to the weapon system, allowances can be made in planning the schedule, cost, and operational support. The intent of the technique, then, is to identify the risks so that they may be recognized and allowances made for them. This done, a critical subsystem is less likely to seriously degrade the availability and capability of the entire weapon system.

IV. CONCLUDING REMARKS

This research task has resulted in a method to quantify the risk connected with the introduction of higher levels of subsystem performance into a weapon system development program. Propulsion subsystems that power aircraft and tactical munitions were used as the initial example. A wide spectrum of propulsion options for tactical missiles are potentially available for the 1990s, when increased propulsion performance capabilities may be required. This method of quantifying the risk associated with such new technologies may be useful in making choices among options.

A data base for man-rated and non-man-rated aircraft turbine engines and for solid rocket motors was constructed to provide a time trend of the state of the art. The technologies were characterized by performance measures believed to be important in developing new engines and motors.

In addition, the non-man-rated air-breathing engines were combined with the solid rocket motors to obtain a model that trends the state of the art of propulsion for tactical missiles, spanning the performance spectrum. It was possible to obtain reasonable time trending of the state of the art for these engines and motors, particularly within individual product classes, such as air-breathing engines or solid rocket motors.

Models were devised to assess risk quantitatively, particularly for homogeneous propulsion types, on the basis of technical characteristics common to all propulsion devices. Less success was obtained in

developing a risk assessment method that spanned non-man-rated air-breathing engines and rocket motors.

Lessons were learned in assembling the data base and performing the analysis leading to the risk assessment method. Identifying the significant performance characteristics of each type of propulsion device to achieve time trending of evolutionary technology improvements, learning how various propulsion options differed in design requirements, obtaining the specific program data required for analysis, and understanding design differences among the propulsion types all proved to be important facets of developing the risk assessment method.

In assessing design characteristics to obtain the parameters that would characterize the technology, we had to understand aspects of the design in considerable detail. For instance, we had to estimate for a number of the solid rocket motors how much of the motor volume was taken up by the blast tube (representing unutilized motor volume), where total impulse divided by total volume was an important variable in the model. The blast tube is required by the missile design, not the motor design; thus, to present a fair comparison of motor capability over the historical time period, we had to subtract the volume of the blast tube from that of the motor where appropriate. This was but one aspect of understanding in considerable detail the designs of the various product classes.

At present, the preferred approach for evaluating risk in specific programs for unmanned applications uses the method associated with the product class, rather than the one that combines types. Thus, solid rocket motors are best evaluated by the model obtained using only the 28 solid rockets in the data base, while air-breathers are best evaluated

by using the model obtained from the 29 man-rated and 9 non-man-rated turbine engines.

Analysis of the data from such models indicates that most programs turn out as might be expected from historical evidence. For the solid motors, for instance, Maverick, operational in the early 1970s, although a boost-sustain motor designed to wide temperature requirements, used a propellant from the Falcon motor developed a decade earlier.

Maverick is considered a very conservative program from the standpoint of then-existing technology, whereas the Falcon program was a technology leader for the time in which it was developed. The risk assessment method indicated that Maverick was conservative and would be expected to succeed technologically. The Maverick propulsion program was indeed very successful.

Among the air-breathers, the F-100 was an advanced man-rated engine for its time (1974). It achieved the highest thrust-to-weight ratio and turbine inlet temperature of any engine to that date. The J 85, an interesting non-man-rated engine, was also very advanced for its time (1957). It achieved the highest thrust-to-weight ratio of any engine to that date, and it experienced considerable difficulty in its development and operational use in the Quail strategic missile.

Since the models aggregate data from a number of manufacturers, they represent industry averages. Thus, it is not possible, particularly where a company contributes only one or a few data points, to assess the company's capabilities. The assessments are based on the entire industry.

A case in point concerning technology trends and company capabilities involves the F-107 engine for the air-launched cruise

missile. A non-man-rated design, it might be considered conservative by 1980 standards because it uses an uncooled turbine, representing turbine inlet temperatures 600 degrees to 700 degrees below the current man-rated technology. However, it was the first turbofan engine to be built by Williams International, a smaller, less experienced turbine engine manufacturer. Thus, although the program does not appear to have a high degree of technological risk with regard to accomplishments by the industry, risk must also be considered in the context of the developer and producer of the product.

Preliminary evaluation of the various models indicates that, for the most part, the results agree with what engineers would expect concerning variables that are important to the trend of the technologies and to the outcomes for particular programs. We believe that the initial results of this task represent a significant step forward in understanding technical trends of performance and risk measures for non-man-rated propulsion for tactical missiles and for man-rated propulsion for aircraft. This exploratory research warrants extension to other subsystems, incorporating schedule and cost considerations in propulsion, and synthesis at the weapon system level.

BIBLIOGRAPHY

I. PLANNING AND RISK ANALYSIS METHODOLOGIES

Armstrong, J. Scott, Long-Range Forecasting: From Crystal Ball to Computer, John Wiley & Sons, New York, 1978.

Bright, James R., Research, Development, and Technological Innovation, Richard D. Irwin, Inc., Homewood, Illinois, 1964.

Deschaines, C. E., and S. Cannon, Least Cost Warfare: Vanguard Methodology Survey, Vol. I, Executive Summary, Computer Sciences Corporation, Huntsville, Alabama, AD-TR-80-52 (AFAL-TR-80-78), July 1980.

Electric Power Research Institute, Methodologies for Characterizing Technologies, prepared by Denver Research Institute, University of Denver, EPRI EA-320, August 1978.

Jantsch, Erich, Technology Forecasting in Perspective, Organization for Economic Co-Operation and Develpment, Paris, 1967.

Martino, Joseph P., Technological Forecasting for Decisionmaking, Policy Sciences Book Series, American Elsevier Publishing Company, Inc., New York, 1972.

McIntyre, John J., Captain, USN (ed.), The Future of Conflict, the Seminar Series of the National Security Affairs Institute, 1978-1979, National Defense University Press, Fort Lesley J. McNair, Washington, D.C. 1979.

Press, S. James, and Alvin J. Harman, with Appendix by Marc Nerlove and S. James Press, Methodology for Subjective Assessment of Technological Advancement, The Rand Corporation, R-1375, April 1975.

Sackman, H., Delphi Assessment: Expert Opinion, Forecasting and Group Process, The Rand Corporation, R-1283-PR, April 1974.

Simons, W. E., G. K. Smith, E. S. Ojdana, Jr., R. Y. Pei, S. W. Purnell, and E. S. Wainstein, Long-Range Development Planning in the Air Force, The Rand Corporation, R-1989-PR, September 1976.

U.S. Air Force, Vanguard, prepared by Air Force Systems Command, DCS/Plans & Programs, Andrews Air Force Base, Washington, D.C. June 1979.

II. THREATS AND SCENARIOS

Brown, Harold, Secretary of Defense, Annual Report Fiscal Year 1982, report ot the Congress on the FY 1982 budget, FY 1983 authorization request, and FY 1982-1986 defense programs, January 19, 1981.

Collins, John M., American and Soviet Military Trends Since the Cuban Missile Crisis, The Center for Strategic and International Studies, Georgetown University, Washington, D.C., 1978.

PRECEDING PAGE BLANK-NOT FILMED

-----, U.S.-Soviet Military Balance: Concepts and Capabilities, 1960-1980, McGraw-Hill Publications Co., 1980.

Collins, John M., and Anthony H. Cordesman, Imbalance of Power, Presidio Press, San Rafael, California, 1978.

Jones, David C., General, USAF, Chairman of the Joint Chiefs of Staff, United States Military Posture for FY 1982, An Overview with Supplement prepared by the Organization of the Joint Chiefs of Staff.

Peterson, Phillip A., Soviet Air Power and the Pursuit of New Militay Options, Studies in Communist Affairs, Vol. 3, published under the auspices of the United States Air Force.

Weinberger, Caspar W., Secretary of Defense, Annual Report to the Congress, Fiscal Year 1983, on the FY 1983 budget, FY 1984 authorization request and FY 1983-1987 defense programs, February 8, 1982.

III. TECHNICAL DATA

A. Propulsion

Hosny, A. N., Propulsion Systems, Revised Edition, Expanded, University of South Carolina Press, Columbia, South Carolina, 1974.

Nelson, J. R., Life-Cycle Analysis of Aircraft Turbine Engines, The Rand Corporation, R-2103-AF, November 1977.

U.S. Air Force, Technical Objective Document Fiscal Year 1982, AFWAL-TR-80-2091, Aero Propulsion Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, December 1980.

B. Other

Gunston, Bill, The Illustrated Encyclopedia of the World's Rockets and Missiles, Crescent Books, a division of Crown Publishers, Inc., New York, 1979.

Jane's Weapon Systems, 1980-81, Ronald Pretty (ed.), Jane's Publishing Incorporated, New York, 1980.

Taylor, Michael J. H., Missiles of the World, Charles Schribner's Sons, New York, 1980.

IV. MANAGEMENT AND ORGANIZATIONAL STUDIES

A. Acquisition

Archibald, K. A., A. J. Harman, M. A. Hesse, J. R. Hiller, and G. K. Smith, Factors Affecting the Use of Competition in Weapon System Acquisition, The Rand Corporation, R-2706-DR&E, February 1981.

Dews, Edmund, Giles K. Smith, Allen Barbour, Elwyn Harris, and Michael Hesse, Acquisition Policy Effectiveness: Department of Defense Experience in the 1970s, The Rand Corporation, R-2516-DR&E, October 1979.

Perry, Robert, Giles K. Smith, Alvin J. Harman, and Susan Henrichsen, System Acquisition Strategies, The Rand Corporation, R-733-PR/ARPA, June 1971.

Rice, Donald B., Defense Resource Management Study, a report requested by the President and submitted to the Secretary of Defense, U.S. Government Printing Office, February 1979.

Smith, G. K., and E. T. Friedman, An Analysis of Weapon System Acquisition Intervals, Past and Present, The Rand Corporation, R-2605-DR&E/AF, November 1980.

U.S. Air Force, Program Management Directive Status Report, November 20, 1980, prepared by Management Policy Division, Directorate for Program Integration, DCS/Research, Development, & Acquisition.

B. Life Cycle

Marks, Kenneth E., H. Garrison Massey, and Brent D. Bradley, An Appraisal of Models Used in Life Cycle Cost Estimation for USAF Aircraft Systems, The Rand Corporation, R-2287-AF, October 1978.

C. Costing

Trainor, Richard James, Study of Factors Leading to Changes in Cost Estimates on Selected Major Department of Defense and National Aeronautics and Space Administration Development Systems, 1977 (originally submitted as a doctoral dissertation).

U.S. Congress, Inaccuracy of Department of Defense Weapons Acquisition Cost Estimates, Ninth Report by the Committee on Government Operations to the Ninety-Sixth Congress, House Report No. 96-656, U.S. Government Printing Office, Washington, D.C., 1979.

V. SYSTEMS STUDIES

A. Weapons and Munitions

Betts, Richard K. (ed.), Cruise Missiles, Technology, Strategy, Politics, The Brookings Institution, Washington, D.C., 1981.

Nelson, J. R., P. Konoske Dey, M. R. Fiorello, J. R. Gebman, G. K. Smith, and A. Sweetland, A Weapon-System Life-Cycle Overview: The A-7D Experience, The Rand Corporation,

R-1452-PR, October 1974.

B. Employment/Deployment

Comptroller General, Effectiveness of U.S. Forces Can Be Increased Through Improved Weapon System Design, Report to the Congress of the United States, PSAD-81-17, January 29, 1981.

C. Force Structure

White, William D., U.S. Tactical Air Power: Missions, Forces and Costs, The Brookings Institution, Washington, D.C., 1974.

VI. STATISTICAL ANALYSIS

Alexander, A. J., and J. R. Nelson, Measuring Technological Change: Aircraft Turbine Engines, The Rand Corporation, R-1017-ARPA/PR, June, 1972.

Barnett, V., and T. Lewis, Outliers in Statistical Data, John Wiley and Sons, Chichester, 1978.

Belsley, D. A., E. Kuh, and R. E. Welsch, Regression Diagnostics: Identifying Influential Data and Sources of Collinearity, John Wiley and Sons, New York, 1980.

Cook, R. D., "Detection of Influential Observations in Linear Regression," Technometrics, Vol. 19, No. 1, February 1977, pp. 15-18.

Cook, R. D., "Influential Observations in Linear Regression," Journal of the American Statistical Association, Vol. 74, No. 365, March 1979, pp. 169-174.

Daniel, C., and F. S. Wood, Fitting Equations to Data, John Wiley and Sons, New York, 1971.

Draper, N. R., and H. Smith, Applied Regression Analysis, John Wiley and Sons, New York, 1966.

Harter, H. L., "Tables of Range and Studentized Range," American Mathematical Statistics, Vol 31, 1960, pp. 1122-1147.

Maddala, G. S., Econometrics, McGraw-Hill Book Co., New York, 1977.

Nerlove, M., and S. J. Press, Univariate and Multivariate Log-Linear and Logistic Models, R-1306-EDA/NIH, The Rand Corporation, 1973.

Newman, D., "The Distribution of Range in Samples From a Normal Population, Expressed in Terms of an Independent Estimate of Standard Deviation," Biometrica, Vol. 31, 1939, pp. 20-30.

Press, S. J., Statistical Estimation by the Empirical Bayes Method: Some Extensions and Logistical Applications RM-4442-PR, The Rand Corporation, 1965.

Pregibon, D., "Logistic Regression Diagnostics," The Annals of Statistics, Vol. 9, No. 4, 1981, pp. 705-724.

Weinschrott, D. J., Polytomous Logit Estimation by Weighted Least Squares, P-5694, The Rand Corporation, 1976.